AN4713
Application note

Induction cooking: IGBTs in resonant converters

Luigi Abbatelli, Giuseppe Catalisano, Rosario Gulino, Maurizio Melito

Introduction

In this paper, we specifically examine the role of STMicroelectronics IGBTs in resonant converters for induction cooking applications. We aim to help designers select the appropriate IGBTs for their circuits by explaining the dependence of IGBT power loss on key parameters, circuit topology and application requirements.

Resonant and quasi-resonant switching techniques have been widely used in high-frequency power conversion systems in order to reduce overall size, weight and power loss *[1]*. To minimize switching losses, resonant and quasi-resonant converters force switching transitions to occur when there is either zero current through or zero voltage across the power switch.

However, the necessary current or voltage rating of the IGBT is much higher than that required for conventional hard-switching systems, so the devices are more expensive. For medium and high power systems, IGBTs with higher current density and low saturation voltages must be selected to minimize the conduction loss.

An induction cooking application is included to evaluate STMicroelectronics IGBT components or to get started quickly with your own induction cooking development project. Induction cooking is not a new invention, it is used all around the world with first patents dating to the early 1900s*[2]*. With recent improvements in technology and the consequent reduction of component costs, induction cooking equipment is becoming increasingly more affordable.

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1 Induction cooking basics

Put simply, an induction cooking element (the equivalent of a "burner" on a gas stove) is a kind of magnetic transformer based on the L-C resonant circuit principle[3], where the inductor, L, is the cooking element itself. When an appropriately-sized piece of magnetically conducting material such as a cast-iron frying pan is placed in the magnetic field created by the cooking element, the field transfers energy into the metal by induction, consequently heating it.

Changing the switching frequency of the high voltage half-bridge driver changes the alternating current flowing through the cooking element, thus allowing the instantaneous regulation of the magnetic field intensity and, consequently, the heating energy.

Figure 1: "Induction cooker plus schematic diagram." shows an example single induction cooker with a schematic diagram on the left. Induction stoves are normally equipped with more than one induction cooking plate.

Figure 1: Induction cooker plus schematic diagram.

Induction cooking has several advantages over traditional methods of cooking:

- speed: the heat transferred to the food is very direct because the cookware is heated uniformly and from within; induction cooking is faster than gas cooking
- safety: there are no open flames so the probability of fire is reduced and the cold stove top is safer for children; the surface below the cooking vessel is never hotter than the vessel itself, only the pan generates heat
- efficiency: according to the U.S. Department of Energy, the energy transfer rating for an induction cooker is 84% versus 74% for a smooth-top non-induction electrical unit and 40% for a gas stove, mainly due to heat transfer loss[4]

An important condition for induction cooking is that cookware must be compatible with induction heating elements; glass and ceramics are unusable, as are solid copper or solid aluminum cookware for most types of cooker. The cookware must have a flat base as the magnetic field drops rapidly with distance from the surface.

If a pot with a thin base is used, the contained liquid boils intermittently, this does not occur on cookware with thicker bases or with better induction cookers. Manufacturers advise consumers that the glass ceramic top can be damaged by impact even though cooking surfaces are required to meet minimum product safety standards regarding impact.

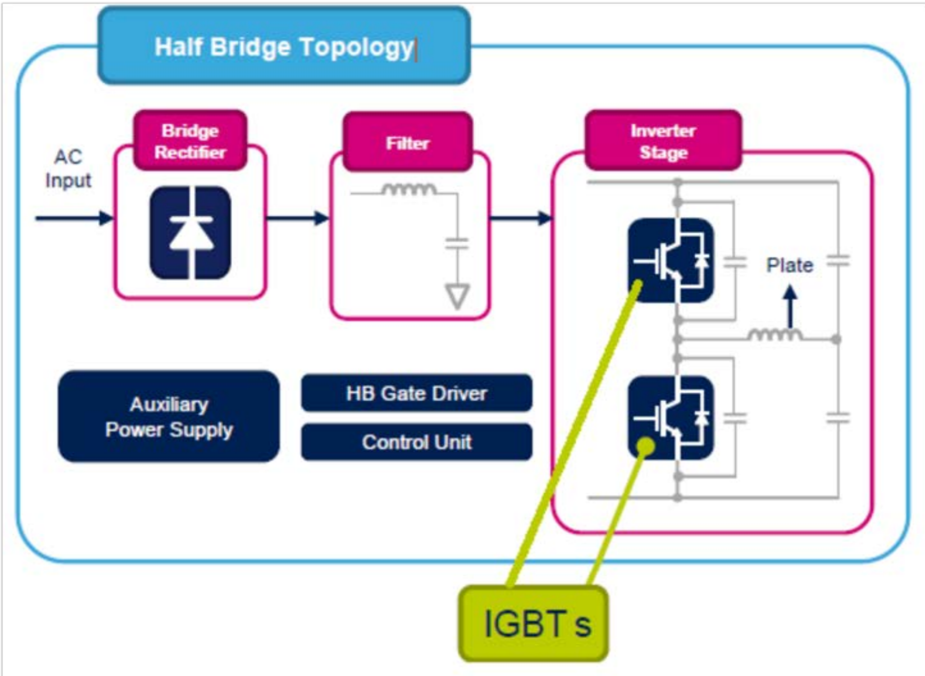
Cheaper induction cookers regulate the transmitted power by simply powering the field intermittently for specific intervals, like most microwave ovens do.

2 Converter topology and power switch requirements

Figure 2: "IGBTs in half bridge topology." shows a half bridge topology commonly used for induction cooking due to the following advantages:

- clamped switch voltages; even if two switches are needed, the required voltage blocking capacity is half that of a single-switch topology
- 50% duty ratio, which simplifies the gate driving circuits and control strategies
- the possibility of implementing Zero Current Switching (ZCS) and/or Zero Voltage Switching (ZVS)
- the ability to use uncontrolled voltage sources

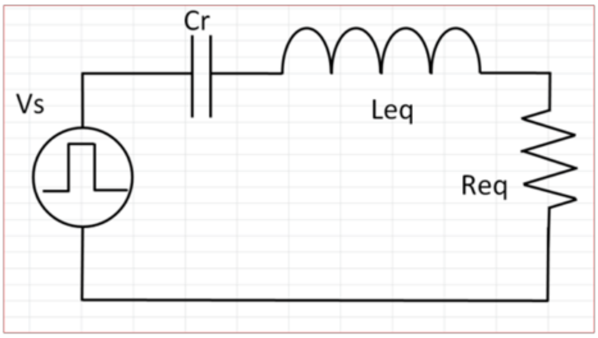
Figure 2: IGBTs in half bridge topology.



The simplified scheme in *Figure 2: "IGBTs in half bridge topology."* shows a voltage-fed half-bridge series resonant inverter consisting of two IGBTs alternating on and off with a duty-cycle of 50% and using a PFM (Pulse Frequency Modulation) technique for output power control. The theory and relevant formulas for series resonant inverters in IH applications are widely available in electronics literature.

In *Figure 3: "Equivalent circuit."*, Leq and Req represent the heating coil and the load, while Cr is the resonant capacitor required for a sinusoidal load current.

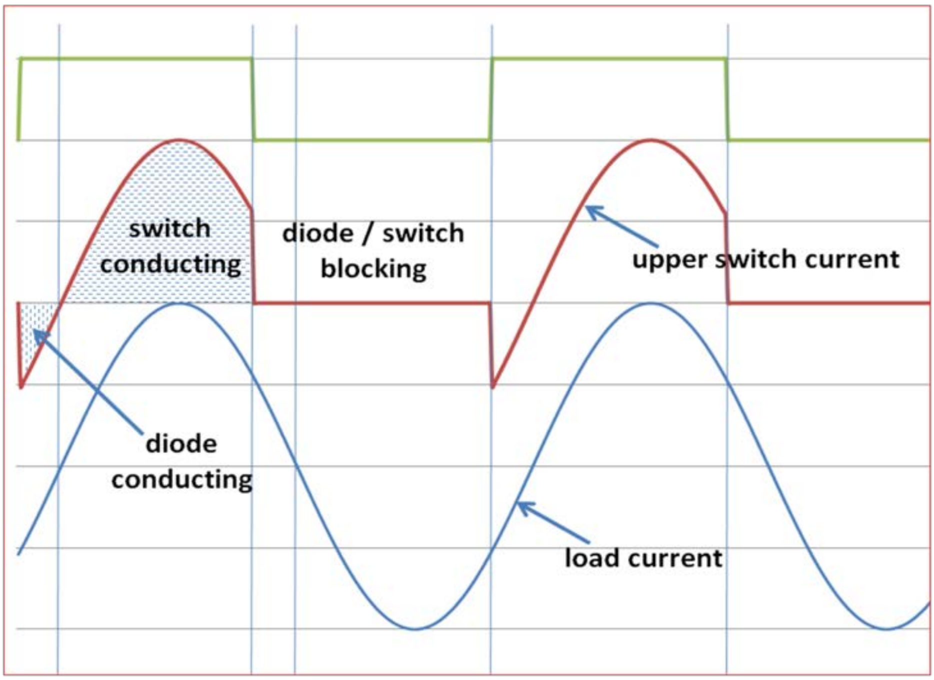
Figure 3: Equivalent circuit.



If the chosen switching frequency is above the resonant frequency, the series resonant circuit behaves as an inductive load and the load current lags the output voltage.

Figure 4: "Simplified inverter stage waveforms" shows the ideal load current (blue line) and the current and voltage on the upper switch. The waveforms of the lower IGBT are not shown but they are easily derived due to the on-off switching symmetry of the upper and lower switch.

Figure 4: Simplified inverter stage waveforms



The main advantages of this approach are:

- no turn-on power loss for both IGBTs and no turn-off power loss for the anti-parallel diode due to the ZCS technique
- maximum output power obtained at the lower limit of the switching frequency, which is above both the resonant frequency and the audible frequency range

The power loss involved is due to anti-parallel diode turn-on (generally negligible), turn-off loss of the IGBT and conduction loss due to anti-parallel diode and IGBT. Hence the need for a fast switching and low $V_{CE(sat)}$ IGBT.

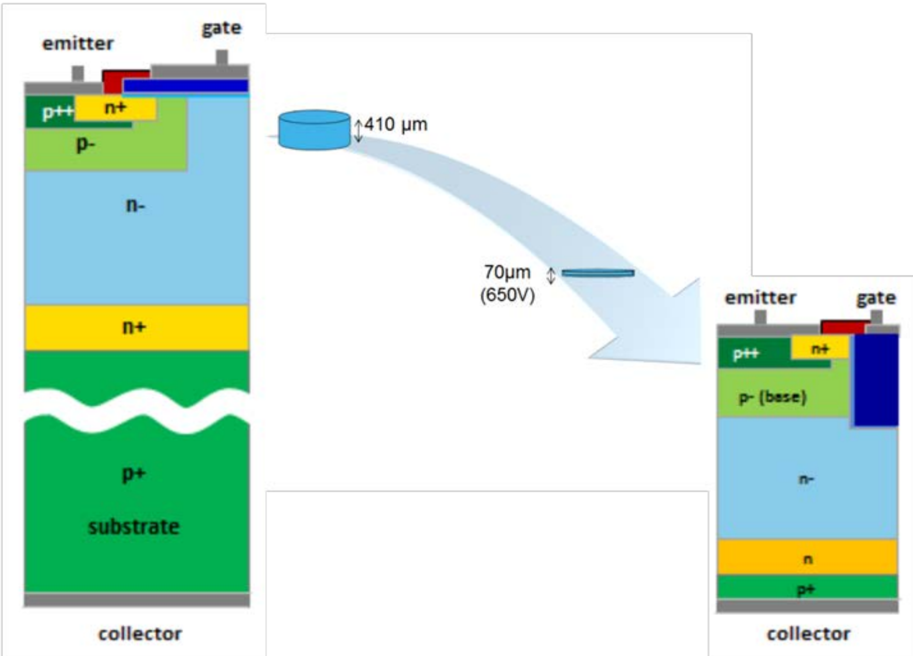
3 IGBT technology advancements

Insulated gate bipolar transistors (IGBTs) combine an easily driven MOSFET gate with the high-current and low-saturation-voltage ability of bipolar transistors, and are quickly becoming the choice for high current and high voltage applications.

Fine balancing of the conflicting switching speed, conduction loss, and ruggedness characteristic and recent technological advancements have brought significant gains in IGBT performance.

Trench field-stop technology offers several advantages over Planar PT including implanted backs-emitter, implanted field stop and trench structure, which offer performance improvements like lower conduction and switching loss, much greater robustness and a significant reduction in thermal resistance (R_{TH}) due to a very thin die, as shown in *Figure 5: "evolution in IGBT technology"*.

Figure 5: Evolution in IGBT technology



To save switching energy during turn-off, the new STMicroelectronics Trench-Gate Field-Stop High-Speed technology minimizes the collector-current tail occurring in all IGBTs during turn-off due to minority-carrier recombination. By significantly shortening the time for the tail current to decay, this technology reduces the associated power dissipation to almost zero.

While optimizing for low switching losses typically impairs the performance of conventional IGBTs in the ON state, our technology also allows a very low saturation voltage $V_{CE(sat)}$ down to 1.6V (typical, at nominal collector current and 100°C). As a result, HB series IGBTs minimize energy loss both during switching and when turned on. Moreover, the

$V_{CE(sat)}$ has a positive temperature coefficient, which allows safer operation of multiple IGBTs in parallel. The technology also boasts minimal parameter variation, which enhances repeatability and can help simplify system design.

Additionally, the high dV/dt capability allows fast and reliable turn-off while minimizing voltage overshoot even when the IGBT is driving a low load resistance. HB series IGBTs are produced on a very thin die, which reduces thermal dissipation from the junction to the case.

HB series devices are ideal for applications like induction heaters, induction cookers, welders, uninterruptible power supplies, power-factor correction, solar inverters and high-frequency power converters. The HB series also features a high maximum operating junction temperature of 175°C, which increases reliability and allows smaller heatsinks and simplifies thermal management. In addition, a wide Safe Operating Area (SOA) boosts reliability in applications where high power dissipation is required.

STMicroelectronics has introduced dedicated IGBTs for soft switching applications like induction cooking systems. The STGW30H60DLFB, STGB30H60DLFB, STGW40H60DLFB, STGWT40H60DLFB, STGWA40H60DLFB, STGW60H60DLFB and STGWT60H60DLFB devices available in TO-247, TO-3P, TO-247 LL and D²PAK packages, combine the benefits offered by the IGBT HB series technology with the benefits offered by the co-packaged diode with low V_F, improving overall systems efficiency.

Table 1: "IGBT characteristics" and *Table 2: "Diode characteristics"* list the main parameters of these IGBTs. For more details, please refer to the relevant datasheet available on *www.st.com*.

Table 1: IGBT characteristics

<table>
<tr><th rowspan="2">Part number</th><th rowspan="2">Package</th><th colspan="9">IGBT characteristics</th></tr>
<tr><th>BV_{CES}</th><th>I_C @ 100°C</th><th>T_J max</th><th>P_total</th><th>IGBT R_{THJ-C}</th><th>$V_{CE(sat)}$ typ @ 25°C</th><th>$V_{CE(sat)}$ max @ 25 °C</th><th>$V_{CE(sat)}$ typ @ 175 °C</th><th>V_{GETH}</th></tr>
<tr><td>STGW30H60DLFB</td><td>TO-247</td><td rowspan="7">600 V</td><td rowspan="2">30 A</td><td rowspan="7">175 °C</td><td rowspan="2">260 W</td><td rowspan="2">0.58 °C/W</td><td rowspan="2">1.55 V (@ 30 A)</td><td rowspan="2">2.0 V (@ 30 A)</td><td rowspan="2">1.75 V (@ 30 A)</td><td rowspan="7">5 V min, 7 V max</td></tr>
<tr><td>STGB30H60DLFB</td><td>D²PAK</td></tr>
<tr><td>STGW40H60DLFB</td><td>TO-247</td><td rowspan="3">40 A</td><td rowspan="3">283 W</td><td rowspan="3">0.53 °C/W</td><td rowspan="3">1.6 V (@ 40 A)</td><td rowspan="3">2.0V (@ 40 A)</td><td rowspan="3">1.80 V (@ 40 A)</td></tr>
<tr><td>STGWT40H60DLFB</td><td>TO-3P</td></tr>
<tr><td>STGWA40H60DLFB</td><td>TO-247 LL</td></tr>
<tr><td>STGW60H60DLFB</td><td>TO-247</td><td rowspan="2">60 A</td><td rowspan="2">375 W</td><td rowspan="2">0.40 °C/W</td><td rowspan="2">1.6 V (@ 60 A)</td><td rowspan="2">2.0 V (@ 60 A)</td><td rowspan="2">1.85 V (@ 60 A)</td></tr>
<tr><td>STGWT60H60DLFB</td><td>TO-3P</td></tr>
</table>

Table 2: Diode characteristics

<table>
<tr><th rowspan="2">Part number</th><th rowspan="2">Package</th><th colspan="8">Diode characteristics</th></tr>
<tr><th>B_{VCES}</th><th>I_C @ 100°C</th><th>T_J max</th><th>P_total</th><th>Diode R_{THJ-C}</th><th>V_F typ @ 25°C</th><th>V_F max @ 25°C</th><th>V_F typ @ 175°C</th></tr>
<tr><td>STGW30H60DLFB</td><td>TO-247</td><td rowspan="7">600 V</td><td rowspan="2">30 A</td><td rowspan="7">175 °C</td><td rowspan="2">72 W</td><td rowspan="2">2.08 °C/W</td><td rowspan="2">1.40 V (@ 30 A)</td><td rowspan="2">1.70 V (@ 30 A)</td><td rowspan="2">1.05 V (@ 30 A)</td></tr>
<tr><td>STGB30H60DLFB</td><td>D²PAK</td></tr>
<tr><td>STGW40H60DLFB</td><td>TO-247</td><td rowspan="3">40 A</td><td rowspan="5">102 W</td><td rowspan="5">1.47 °C/W</td><td rowspan="3">1.55 V (@ 40 A)</td><td rowspan="3">1.80 V (@ 40A)</td><td rowspan="3">1.25 V (@ 40 A)</td></tr>
<tr><td>STGWT40H60DLFB</td><td>TO-3P</td></tr>
<tr><td>STGWA40H60DLFB</td><td>TO-247 LL</td></tr>
<tr><td>STGW60H60DLFB</td><td>TO-247</td><td rowspan="2">60 A</td><td rowspan="2">1.80 V (@ 60 A)</td><td rowspan="2">2.10 V (@ 60 A)</td><td rowspan="2">1.50 V (@ 6 0A)</td></tr>
<tr><td>STGWT60H60DLFB</td><td>TO-3P</td></tr>
</table>

The STGW40H60DLFB was tested in a 3 kW resonant converter (according to the schematic in *Figure 2: "IGBTs in half bridge topology."*), using generic cookware for induction cookers. The STGW60H60DLFB is advisable for induction cooking systems rated at greater than 3 kilowatts.

The 650 V HB series IGBTs STGW40H65DFB, STGWT40H65DFB, and STGWA40H65DFB may also be suitable for certain application requirements.

4 Analysis of STGW40H60DLFB

Our analysis revealed the dynamic performance of the STGW40H60DLFB in a 3 kW current resonant converter for induction cooking applications.

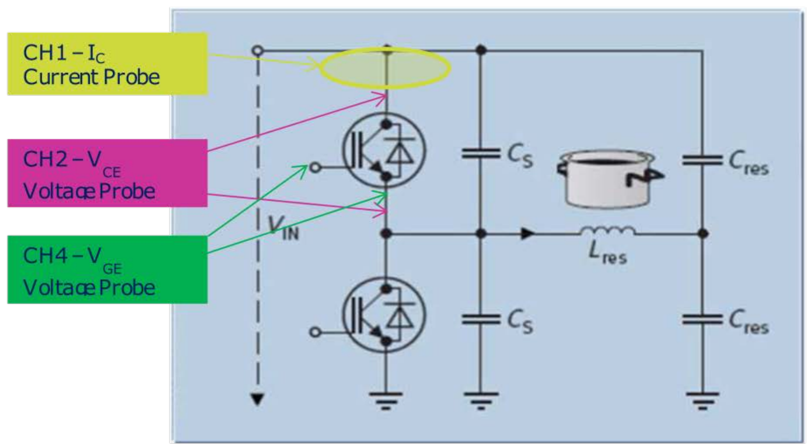
The following test conditions were applied:

- ambient temperature T_{AMB} = 25 °C (±2 °C)
- all the tests used a generic pot for induction cookers, with power ranging from 1 to 3 kW
- the IGBTs and the diode bridge rectifier (shown in *Figure 2: "IGBTs in half bridge topology."*) were screwed on the same heatsink and ventilated by an external fan
- the system was maintained in optimum heat dissipation conditions with a properly connected fan and the cooker placed on a solid support away from any barriers or walls which could inhibit air flow
- a thermal camera was used to measure the case temperature with reasonable accuracy
- Other test parameters include:
  - switching frequency, variable from 22 to 34 kHz (up to 3 kW)
  - resonant capacitors, $C_{RESONANT}$ = 680 nF
  - snubber capacitors, $C_{SNUBBER}$ = 33 nF
  - resonant inductor, $L_{RESONANT}$ = 80 µH @ 10 kHz no load
  - Power = 1 to 3 kW
  - I_{OFF} = 25 to 39 A

Snubbers are frequently used in electrical systems with an inductive load where the sudden interruption of current flow leads to a sharp rise in voltage across the current switching device in accordance with Faraday's law*[5]*. These transients can cause electromagnetic interference (EMI) in the circuits.

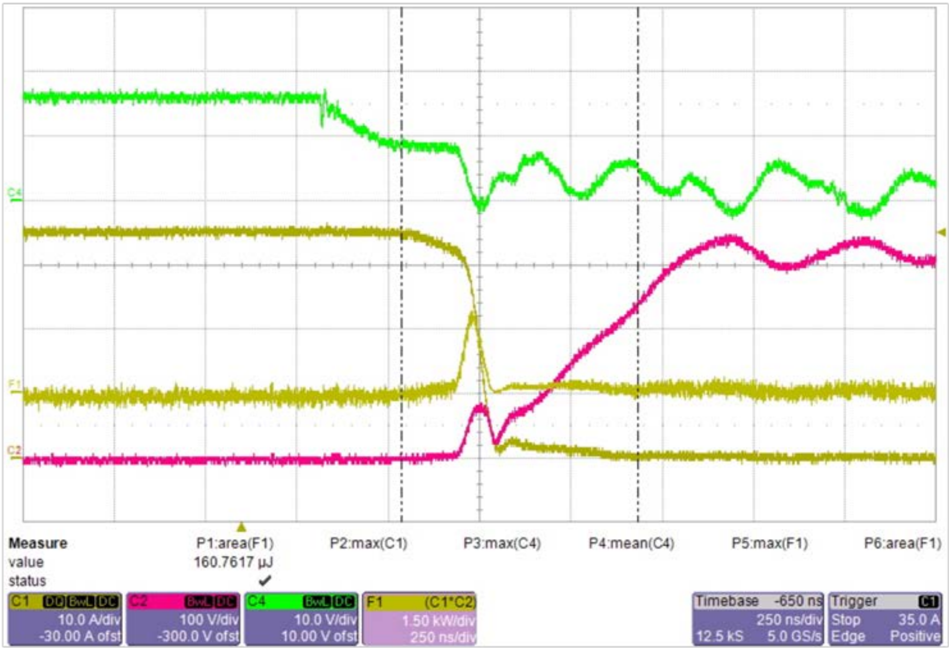
Figure 6: "Half bridge topology with voltage and current probe placement" shows the elementary power section and the position of the voltage and current probes to acquire the STGW40H60DLFB waveforms during turn-off.

Figure 6: Half bridge topology with voltage and current probe placement



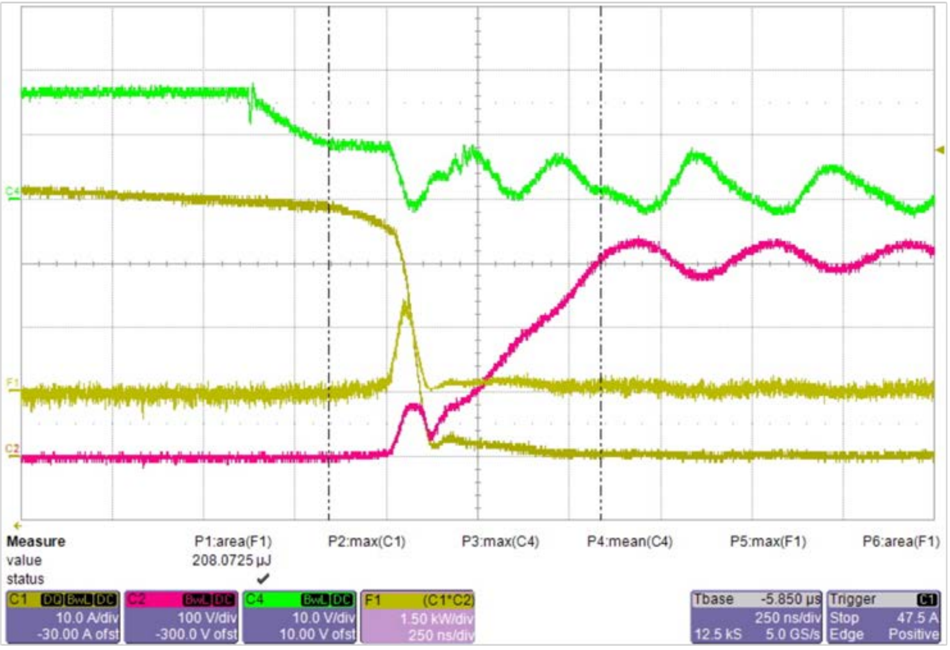
The turn-off waveforms in *Figure 7: "STGW40H60DLFB turn-off waveform, Power = 1 kW, $C_{SNUBBER}$ = 33 nF"* show the behavior of the STGW40H60DLFB at 1 kW under the test conditions described above.

Figure 7: STGW40H60DLFB turn-off waveform, Power = 1 kW, $C_{SNUBBER}$ = 33 nF



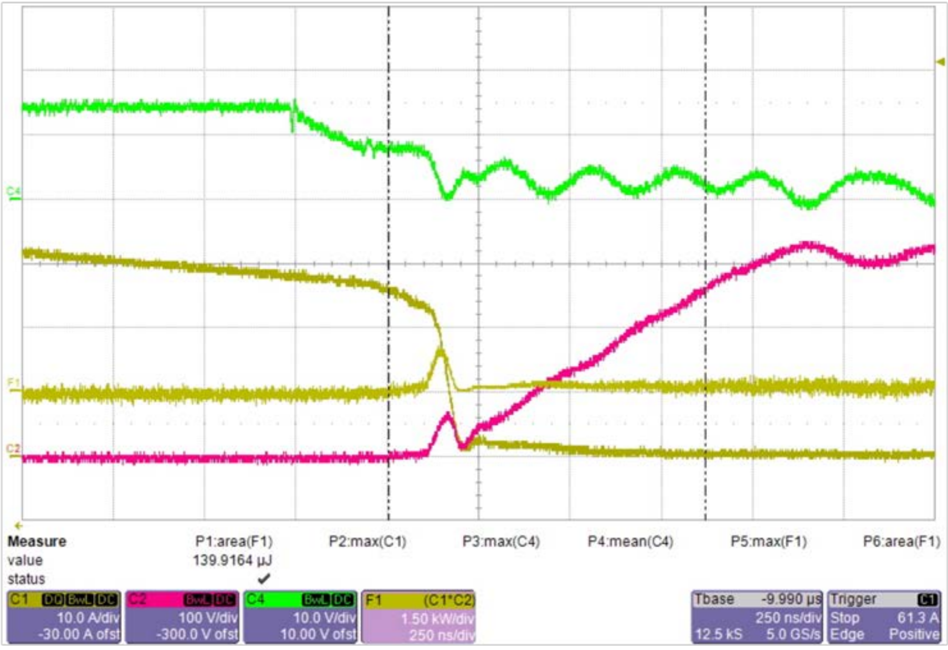
The turn-off waveforms in *Figure 8: "STGW40H60DLFB turn-off waveform, Power = 2 kW, $C_{SNUBBER}$ = 33 nF"* show the behavior of the STGW40H60DLFB at 2 kW under the same test conditions.

Figure 8: STGW40H60DLFB turn-off waveform, Power = 2 kW, $C_{SNUBBER}$ = 33 nF



The turn-off waveforms in *Figure 9: "STGW40H60DLFB turn-off waveform, Power = 3 kW, $C_{SNUBBER}$ = 33 nF"* show the behavior of the STGW40H60DLFB at 3 kW under the same test conditions.

Figure 9: STGW40H60DLFB turn-off waveform, Power = 3 kW, $C_{SNUBBER}$ = 33 nF



5 Analysis of measured data

The measured data in *Table 3: "Measured test data for the STGW40H60DLFB"* was obtained by varying the input power (from 1 to 3 kW) for STGW40H60DLFB with $C_{SNUBBER}$ = 33 nF. T_{AVG} is the average temperature between the case temperature of high and low side IGBTs.

Table 3: Measured test data for the STGW40H60DLFB

Tested Device	P_{IN} (kW)	T_{AVG} (°C)	I_{OFF} (A)	I_{PEAK} (A)	E_{OFF} (µJ)	fsw (kHz)
STGW40H60DLFB	1	55	35.3	35.3	160.8	33.8
	2	75	28.1	48.5	208	26
	3	91.5	25.5	62.3	140	22

The relative IGBT and diode contributions to total power dissipation (during IGBT and diode conduction and during IGBT turn-off) are provided in *Table 4: "Breakdown of power loss in the STGW40H60DLFB"*.

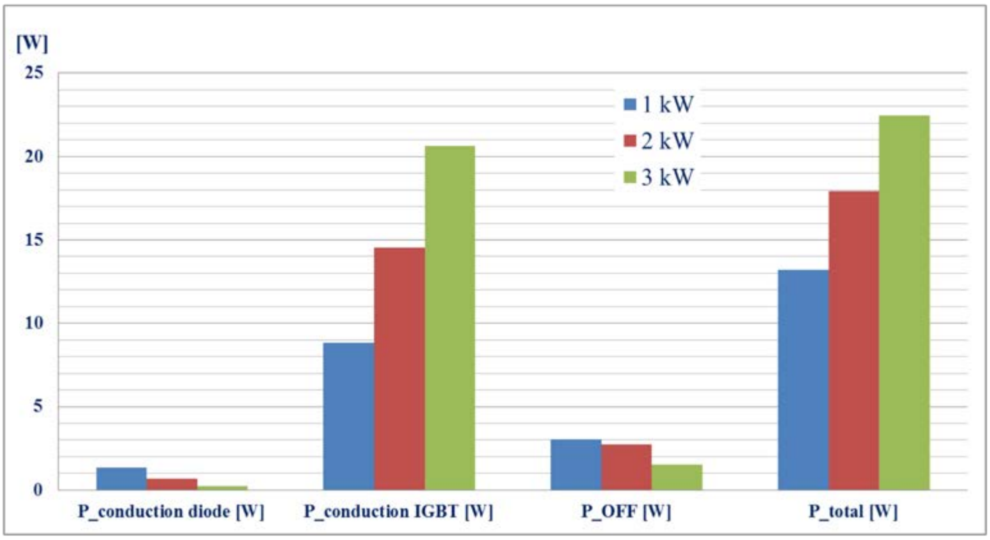
The data clearly shows that the conduction loss of the IGBT is the biggest contributor to total IGBT plus diode power loss across the entire power range and should therefore be limited as much as possible.

Table 4: Breakdown of power loss in the STGW40H60DLFB

Device	P_{IN} (kW)	P_conduction diode (W)	P_conduction IGBT (W)	P_OFF (W)	P_total (W)	T_{AVG} (°C)
STGW40H60DLFB	1	1.34	8.83	3.04	13.21	55
	2	0.67	14.52	2.73	17.92	75
	3	0.25	20.65	1.54	22.44	91.5

The chart in *Figure 10: "Power loss contributions in STGW40H60DLFB"* provides a graphical representation of the above data.

Figure 10: Power loss contributions in STGW40H60DLFB



6 Conclusions

The test results for the 600 V breakdown voltage class of HB series IGBTs in a resonant converter evidenced the high performance of these devices due to an optimal trade-off between $V_{CE(sat)}$ and E_{OFF}.

The Field-Stop High-Speed technology in these new HB series IGBTs allows significant limitation of conduction and switching losses.

IGBT products with a 650 V breakdown voltage are also suitable for certain induction cooking system applications.

7 Bibliography

[1] R. Letor, S. Musumeci, F. Frisina, “IGBTs in resonant converters”, STMicroelectronics, AN662, December 1994.

[2] see, for example, UK Patent Application GB190612333, entitled "Improvements in or relating to Apparatus for the Electrical Production of Heat for Cooking and other purposes", applied for by Arthur F. Berry on 26 May 1906.

[3] STMicroelectronics, AN2383, “A single plate induction cooker with the ST7FLITE09Y0”, September 2009.

[4] "Technical support document for residential cooking products. Volume 2: Potential impact of alternative efficiency levels for residential cooking products. (see Table 1.7). U.S. Department of Energy, Office of Codes and Standards." (PDF). Retrieved 2011-12-06.

[5] Faraday, Michael; Day, P. (1999-02-01). “The philosopher's tree: a selection of Michael Faraday's writings”.

8 Revision history

Table 5: Document revision history

Date	Revision	Changes
03-June-2015	1	Initial release.